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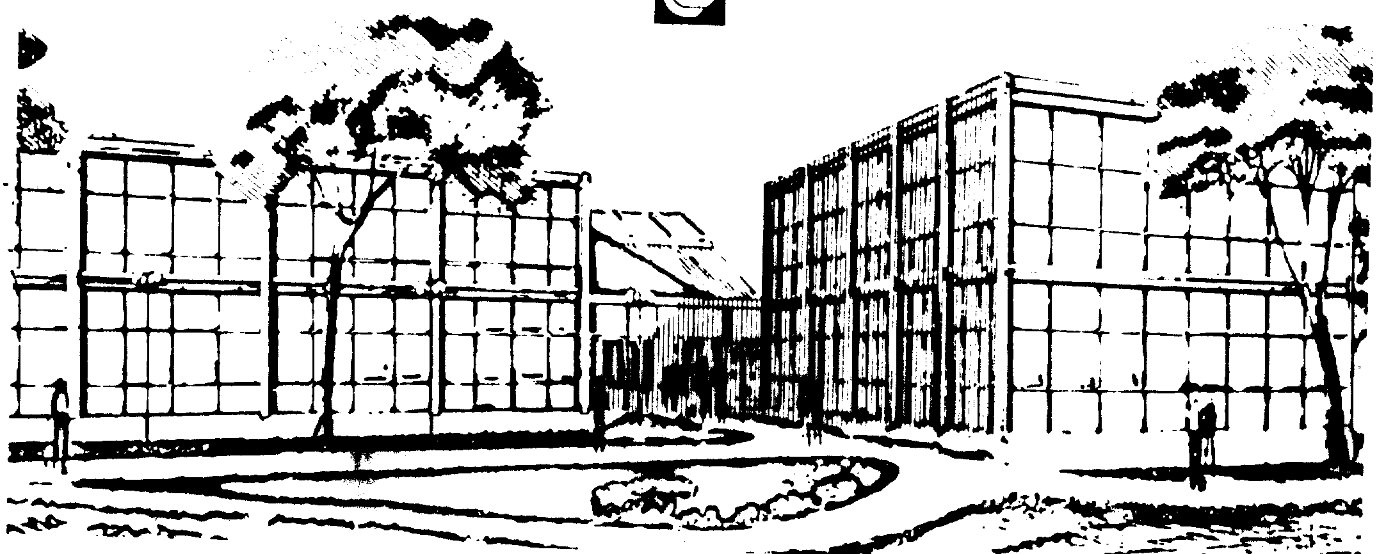

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ABSTRACT

Finite element modeling of underground formations has been used by several researchers in attempts to calibrate models of or to predict subsidence due to in-situ coal gasification. Due to the non-linear nature of soil and rock (and material in between) it is desireable to allow for non-linear analysis. Doubtless the higher costs and limited availablility of non-linear finite element analysis have forced some investigators to use linear elastic analysis of subsidence models where non-linear analysis would have been more appropriate. At Lawrence Livermore Laboratory several good computer codes are in regular use for inelastic analysis and we have taken advantage of this capability in support of the Hoe Creek gasification experiments.

This paper discusses our approach to including non-linear effects in the subsidence models we have been working with. In addition we have calibrated some computer models against both field measurments and elastic theory. We have included spalling of overburden rocks in the cavity growth process and we are investigating the coupling of mechanical with thermal effects in order to predict the extent of overburden spalling.

PROGRAMS AT LLL

Our experience at LLL is with three non-linear finite element programs all based to some degree on the SAP , NON-SAP family of programs developed at University of California, Berkeley. SAP IV [1] is known to many as a general linear, elastic program which has been adapted and implemented into many forms. NON-SAP [2] was derived from SAP IV as a non-linear program with limited capacity. It too has been altered and re-configured , and actually re-written by its original authors as well.

The three codes we have used (to various degrees) are called ROCK3D, NSAP2D, and ADINA. The first program is our implementation of the Agbabian code [3] developed for the U. S. Bureau of Mines. It processes general three dimensional problems with a built-in mesh generator of the 'logical cube' variety. Two dimensional problems are treated as a sub-set of the three dimensional case; a band-width minimizer is incorporated in the program, and large problems are structured to use a file resident equation solving process. ROCK3D is tailored to rock problems in the material descriptions and in the specialized output. Displacements, stresses and strains may be printed for either total loading or for changes since application of gravity loads on the model. Elements may be inserted in the model or removed from it during the analysis to simulate embankment and excavation processes.

The material models in the Agbabian code require special attention at this point. The available materials are well oriented to the various properties of rock and soil. Basically the material can have constant or variable modulus, with or without plasticity, with or without a cap. Both isotropic and anisotropic cases can be used,and provision is made for visco-elastic and visco-plastic conditions. Not all choices can be used simultaneously, of course, but in general we can model the material with greater precision than we can characterize geologic materials by means of laboratory tests. That is we must make some assumptions when filling-in the blanks of the material property tables. ROCK3D also provides slip joints to model known faults if necessary. No thermal effects may be modeled, however.

The second program is called NSAP2D [4] which, as its name implies, is a two-dimensional version of NON-SAP specially adapted at Lawrence Livermore Laboratory by John Hallquist. This program contains some special material models and element integrations to eliminate the hour-glassing problems in axisymmetric elements which under go substantial deformations. There is also a very good slip-line or joint element in NSAP2D. However the program is not particularly aimed at soil and rock problems and it lacks the capability of adding and removing elements to simulate excavation and embankment sequences at the present time. Our use of NSAP2D is limited to calibration and comfirmation against the other programs.

The third code which we use is called ADINA [5]. This program is the newest re-write of NON-SAP done by Professor Bathe, now at M.I.T. (formerly at U.C. Berkeley). ADINA cures some of the draw-backs of NON-SAP particularly with respect to problem size. ADINA is a much more sophisticated code than its predecessor, but then it is several years newer. It handles general 3-D problems with bar, beam, planar, and brick type elements. No mesh generator is built-in so we have implemented a logical cube mesh program to build the large, graded meshes appropriate to underground problems. ADINA does provide for either adding or removing particular elements during the solution process, but unlike ROCK3D a given element may not be both added and removed, nor is there a rock yield cap model at the present time.

The material models in ADINA include linear elastic, thermo-elastic, variable modulus with or without tension cut-off, concrete (or rock-like) with tension cut-off, Drucker-Prager plastic (like a Mohr Coloumb) which is a cohesion and internal friction model, four types of von Mises plasticity with and without viscous effects and with two types of strain harening, and provision for a 'user-defined' material. Like the first code, more capability exists than we can adequately expect to use due to our very limited knowlege of the behavior of rock mass subjected to large deformations.

Since ADINA is much newer than NON-SAP and since it is also designed for large problem capacity, we have found that it is in general more cost-effective than the other codes even though each of the two others has certain special features.

In summary of this discussion of codes, we would like to say that all three of the non-linear programs have, in general, more power in the material models than we can effectively use with our limited knowlege of underground mechanics. We are forced to make broad assumptions as to the process of formation of an underground cavity, its shape, and the mechanisms by which material on the sides and overhead of the cavity may spall or otherwise not participate in the structural continuity. It is these assumptions and the rationale behind them which constitute the body of this paper.

EXCAVATION SEQUENCING

In order to simulate plastic flow, crushing, and other assumed non-linear effects during the formation of a gasification cavity, it is necessary to assume dimensions and sequences for the ordered removal of material elements. As elements are removed the overburden weight is borne solely by the remaining elements which deform elastically if possible, or inelastically in accordance with a material constitutive rule. In general, our knowlege of what is happening to the cavity during the gasification process is derived from instrument read outs plus calculations of the gross volume of coal consumed. Borings after the gasification experiments can potentially measure the final cavity size and shape but do not indicate the order or rate of growth of the cavity, particularly the rate at which overburden material collapses into the coal cavity itself. In a series of finite element analyses during the Fall of 1976 Lawrence Livermore Laboratory engineers [6] used the ROCK3D program to explore the probable magnitude of surface motion due to the first Hoe Creek gasification experiment. The cavity shape was taken to be simply a right circular prism corresponding to the anticipated volume of coal to be burned; no overburden interaction was assumed at that time.

In the spring of 1977 we again used the ROCK3D program to investigate subsidence, this time for the second Hoe Creek experiment [7]. In this second series of analyses we removed that portion of the overburden material which indicated any amount of tension during the analysis (fig. 1) . No significant changes in surface subsidence appeared due to this additional removal of material since very little elastic energy was being held in the tensile region. During the summer of 1977 we explored some elasticity solutions for cavities and verified the extent of the tensile region which was indicated by the computer program. With both the finite element and 'exact' solutions in front of us, we were very confident that the tensile region was well defined (and very small) and that the region of material which should collapse into the coal cavity was also well defined. This turned out to be not the case, however, since the second Hoe Creek experiment yielded a very much larger region of overburden spalling than can be explained by induced tension.

Since this much larger collapsed zone can not be explained by mechanical effects, even non-linear effects, the gasification process itself is the probable cause of the much larger spalled region . The overburden at Hoe Creek is largely comprised of clays and claystones which are saturated, have low permeability, and are subject to shrinkage

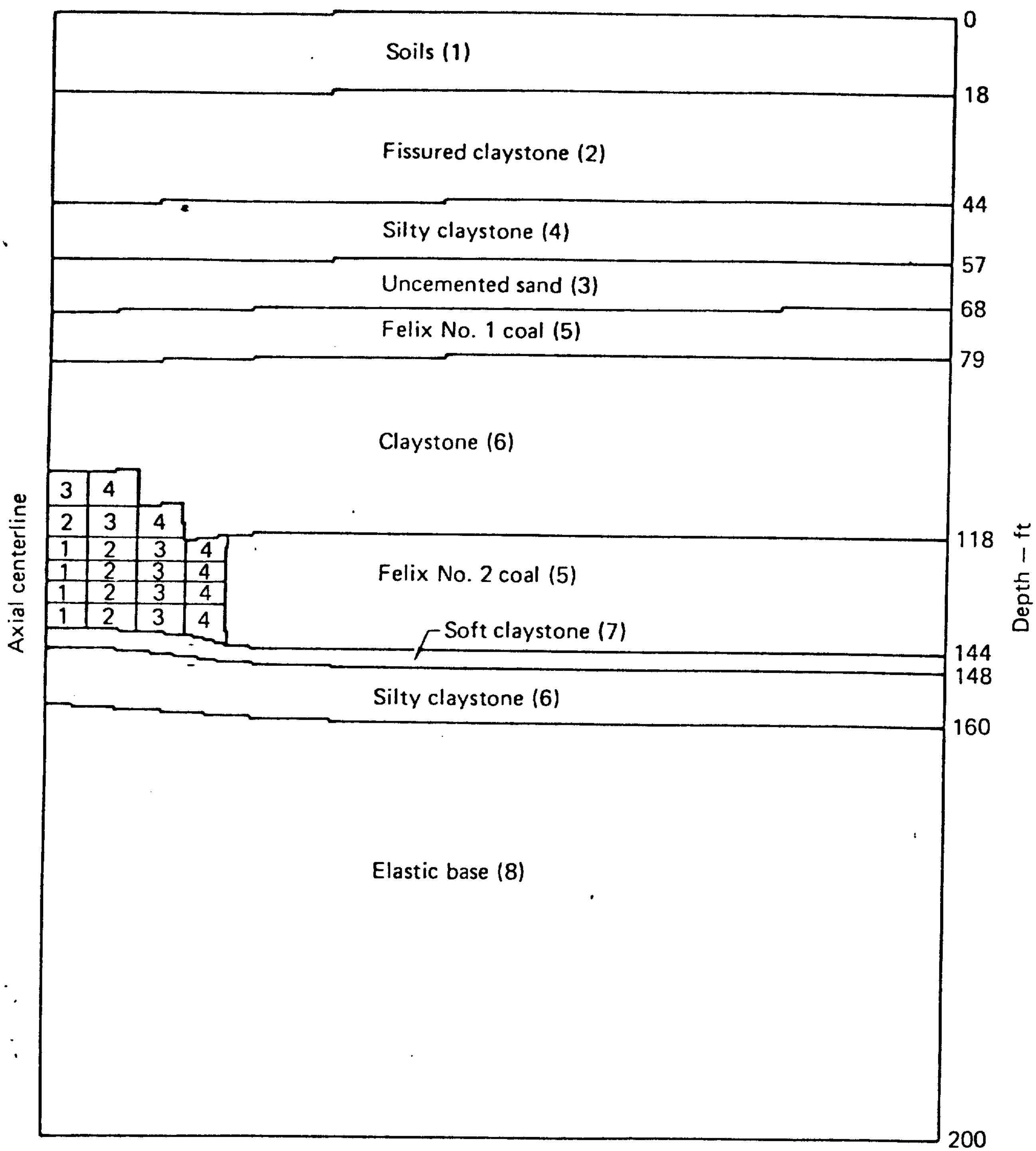

Fig. 1. Outline of axisymmetric finite element model for Hoe Creek Site II. The simplified cylindrical model represents a teardrop-shaped cavity with maximum dimensions of 50 ft by 80 ft. Vertical displacements in strata are shown exaggerated ten times. Numbered sections at the left of the Felix No. 2 Coal seam show the element excavation sequence. Numbers in parentheses are material numbers.

when dried by the hot gasses of the process. Charles Thorsness of the Lawrence Livermore Laboratory wrote a simple expression for the rate of drying of a porous medium given the thermal properties and porosity of the material [8]. Based on observations by Harold Ganow of natural coal outcrops which have burned by natural events, a size of 'clinker' was assumed, and this dimension was introduced into the rate-of-drying expression. The result is a characteristic time-to-spall for clinkers of some assumed size, from clays of assumed properties. When using some reasonable values for the clays at Hoe Creek Thorsness' formula yields a gross height of overburden spall which corresponds rather nicely with our present estimate of the final cavity size from the second Hoe Creek experiment.

We have recently taken this new mechanism of spalling, and incorporated it into our subsidence model (fig. 2). This new and larger cavity has been analysed using ADINA in a new series of computer runs. The surface subsidence agrees fairly well with field measurments (0.03 feet maximum) particularly when we use some new values of material stiffness and strength derived from an extensive series of core tests. Very little non-linear action is taking place in this revised model as contrasted with earlier analyses which showed considerable plastic deformation. We attribute the lessened degree of plasticity due to the well domed shape of the cavity, which is a tension free, self supporting structure.

While using our current estimate of the actual cavity (and getting agreement as to surface displacement) is good for calibration of the computer model and material properties, it does very little for developing a capability of prediction, per se, in advance of an experiment or a production burn. We can estimate the rate at which clays will dry and spall into the cavity, but if carried to a logical conclusion one can expect that the spalling process must terminate at some point in time and space; our recent thoughts are that at some point in height above the cavity floor the compressive stresses are sufficient to prevent the clays from forming open cracks as they dry. That is, at some value of compressive stress the tensile strain due to drying will not be sufficient to yield a net tensile strain, hence no crack will form and the material will cease spalling. If we can validate this theory then a better predictive tool may emerge, one which will define the limits of the gross cavity given some material properties and overburden loadings. We intend to work in this direction for the balance of the fiscal year, using Hoe Creek experiments as a frame of reference.

ELASTICITY SOLUTION

We mentioned earlier that we had an elasticity solution which provided a check on the theoretical zone of tension due to the formation of a void in the coal layer. This solution is based on the work of Raymond Mindlin [9] for the case of a circular tunnel in a gravitating half-space. There is also a solution for a spherical cavity, but this second case was published in Polish and the reviewer said that it did not treat the ground surface (a stress free surface) correctly.

We used the solution of Mindlin and expanded it for ranges of native latteral pressure, depth, radius, and poisson's ratio. Mindlin originally solved the problem with a numerical series with either a slide rule or a desk calculator, in either case he was limited in the number of terms which could be included; we expanded the series to 80 terms (instead of three or four) and solved hundreds of combinations on a digital computer. We then plotted the results so as to display hoop stress around the cavity surface as a function of cavity geometry (depth to radius ratio), stress ratio (latteral pressure to vertical pressure), poisson's ratio, and position within the cavity. We expressed latteral pressure as a fraction (or multiple) of vertical pressure and plotted the stress as a fraction of

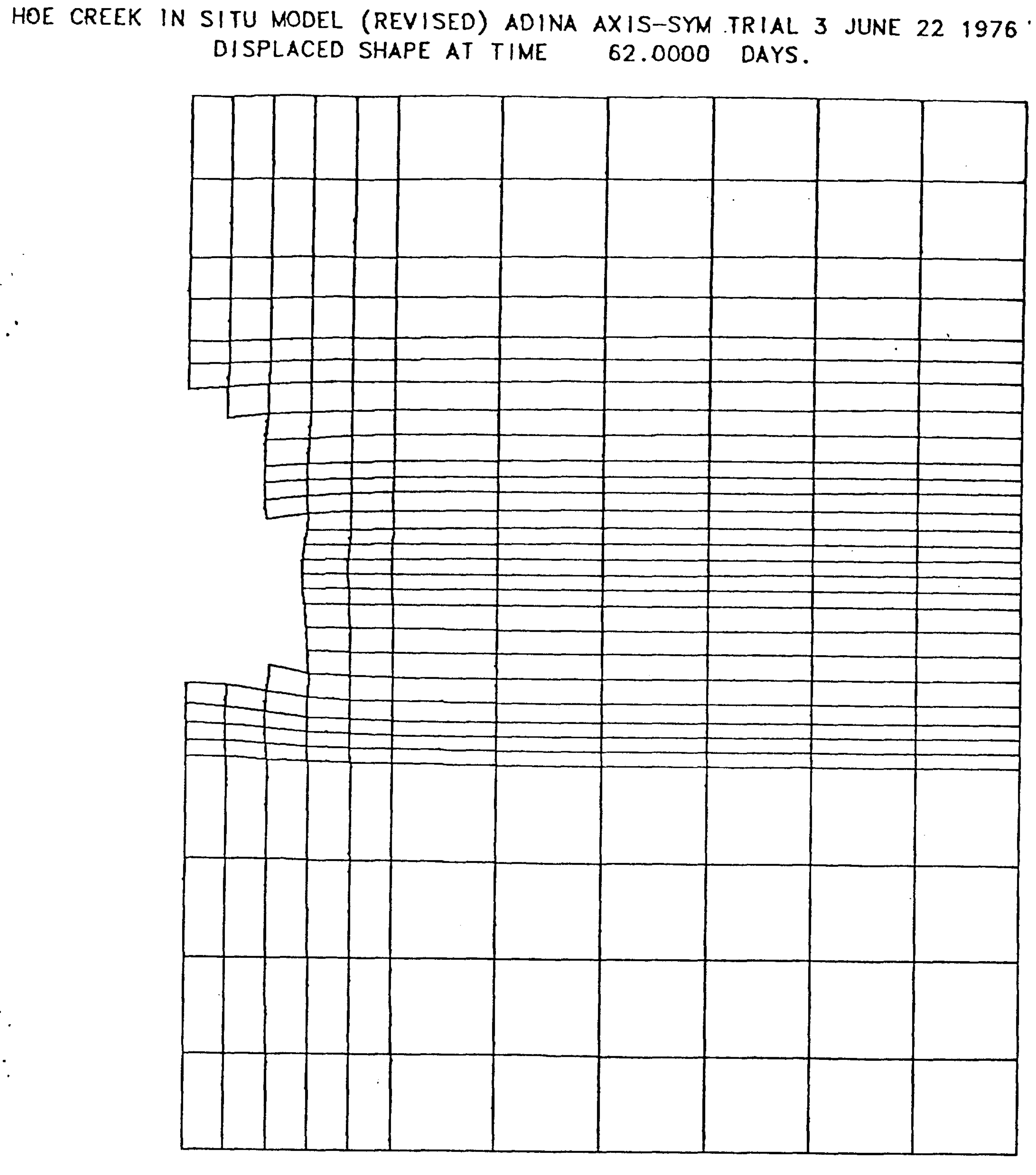

Fig. 2. Deformed mesh at two time steps after removal of final elements of overburden. This mesh includes revised spalling sequence and revised strati-graphic column. Displacements shown exagerated by a factor of 10.

vertical pressure also. The resulting plots are non-dimensional, and clearly indicate the cavity geometries where tension does and does not occur. In fig. 3 tension occurs for the case of depth/radius ratios between 0.1 and 0.8, but for shallower and deeper cavities no tension occurs. Note that this figure is for poisson's ratio of 0.3 and where latteral pressure is six-tenths of vertical pressure. In fig. 4, where latteral pressure is equal to vertical pressure a zone of tension occurs at 30 degrees from center line , but only for very shallow cavities (d/R about 0.05). In general low values of latteral pressure imply an increased occurance of tension in the cavity roof, and high values of latteral pressure imply less or no tension in the roof but greater occurance of tension in the side walls. At the Hoe Creek site we suspect a high value of latteral pressure exists, which aids the effect of a free-standing arch roof.

To determine the height of a stable cavity we use an indirect process. We assume that any material in tension does not contribute to the structural continuity of the body (an elastic analytical solution can not handle this condition) so we must revise the diameter of the cavity until a cavity is found which is free of tension. The increase in cavity dimension necessary to make it tension-free indicates the minimum stable cavity extent. In order to simplify the calculation of cavity dimension in this process, we assumed a cavity with a shallow parabolic roof, and we can then relate the instantaneous curvature at the apex of the roof to the height and width of the parabola at any point. We took the liberty of assuming that the parabolic roof did not violate the elastic analytical assumption to any significant degree. Noting that a definite ratio of depth-to-radius indicates the tension-free point, we can then simply take this minimum depth/radius value and substitute it into the parabolic formula to get the height of the cavity.

For the case of the Hoe Creek computer runs of 1977 we obtained very good agreement between the cavity shape with tension elements removed (fig. 1), and the tension-free cavity predicted by Mindlin's solution with our parabolic roof assumption. This work is discussed in greater detail in reference [7].

NONLINEAR MATERIAL PROPERTIES

For the inital work in 1976 no material property data were available, but this improved in 1977 when some core tests were completed; recently a full complement of triaxial tests have been completed on the overburden rocks and soils at Hoe Creek. These latter data along with improved strati-graphic information have given us a better model of the actual site of the second Livermore experiment. This experiment was extensively instrumented, as will be reported to you by Harold Ganow during session VI of this conference [10].

In 1976 Langland and Fletcher [6] used nonlinear, elastic properties for the majority of the materials, and elastic-plastic properties for the region identified as clay. No attempt was made at that time (or since) to model such effects as creep and strain hardening (or softening) nor thermal strains.

For the analysis series in early 1977 we had some material strength data from the site, as well as an approximate strati-graphic column. The material test data indicated that elastic-plastic properties fit the site materials, using a cohesion-and-friction model known as Mohr-Coloumb or Drucker-Prager. This model differs from a simple non-linear elastic model in that the material is allowed to flow plastically along a so-called yield surface once the loading is sufficiently severe on an element of material. The yield surface is either a cylindrical prism with its axis on a line of equal principal stresses (hydro-static stress state) which is equivalent to a simple yield strength (no internal friction) or the yield surface may be a conical prism which expands as the mean

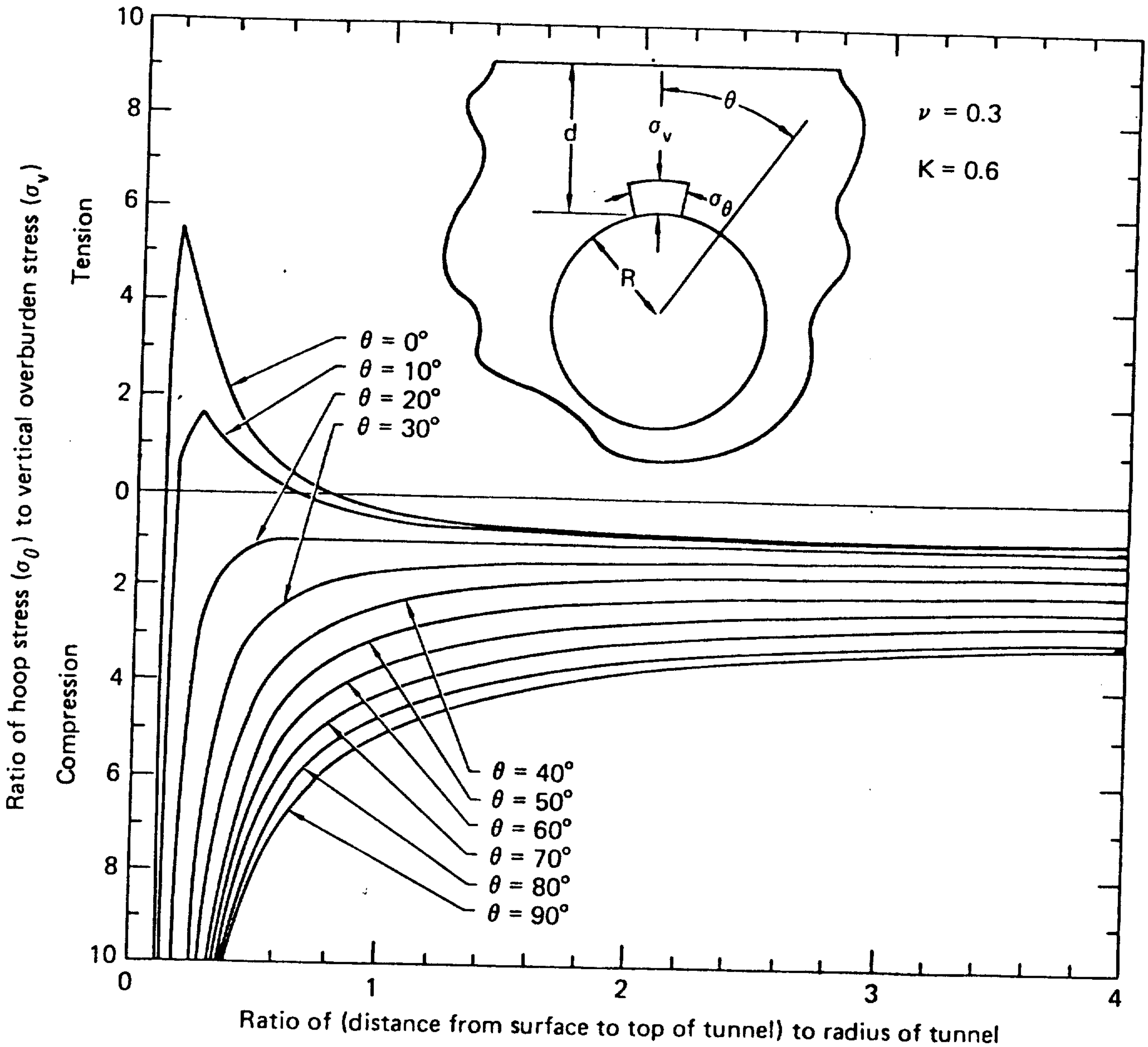

Fig. 3. Stress in the roof of a circular tunnel at various angles (θ) from the vertical. Stress is shown as a function of d/R, where d = distance from the surface to the top of the tunnel, R = radius of the tunnel, ν = Poisson's ratio, K = ratio of horizontal to vertical <u>in situ</u> stresses.

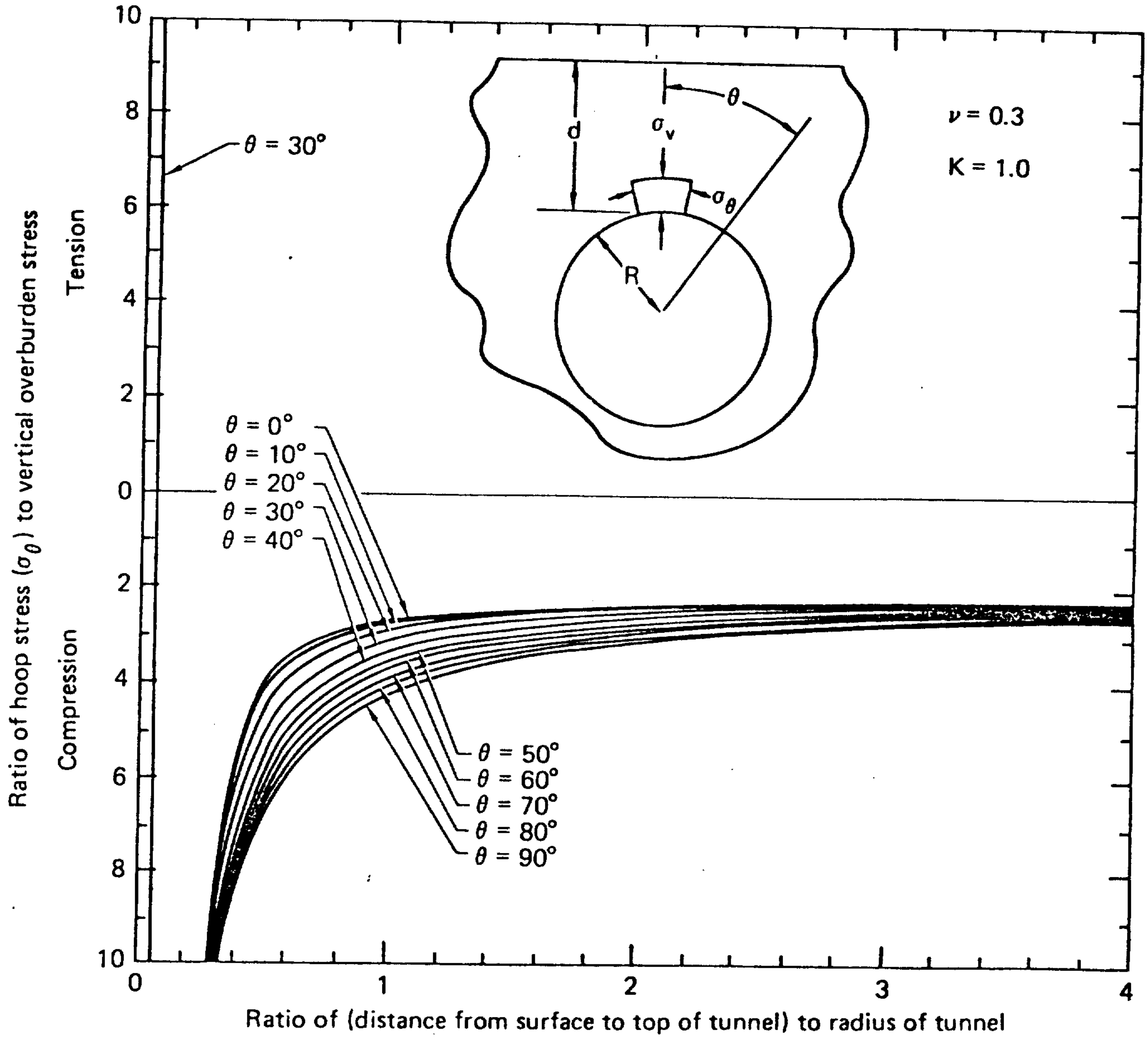

Fig. 4. Stress in the roof of a circular tunnel at various angles (θ) from the vertical. Stress is shown as a function of d/R, where d = distance from the surface to the top of the tunnel, R = radius of the tunnel, ν = Poisson's ratio, K = ratio of horizontal to vertical *in situ* stresses.

normal stresses become more compressive, thus implying internal friction added to cohesion. In practice we may set either the cohesion or the friction to zero and thus adjust between course, granualar materials like sand, and cohesive materials like clay which exhibit little or no internal friction between particles. In the case of the ROCK3D program we may also orient the yield surface so as to include non-isotropic materials, but this feature requires more material data than we possess at the present.

The Mohr-Coloumb material combines the effects of cohesion with internal friction on the compressive side of the stress axis and thus effectively weakens the material for conditions of one or more directions of tensile stress. This is not a true tension cutoff, but the effect is that large deformations would occur in the event of tension loading; this is adequate if one does not object to plastic flow in place of crack propogation. Two of the nonlinear programs available to us provide for true tension cutoff and crack growth, however we believe that this is more applicable to hard, brittle materials rather than to the softer materials which we have to model at Hoe Creek. Further, use of the tension-cutoff material model prohibits plastic flow in the same material, therefore we prefer to accept a small error in tension and use the Mohr-Coloumb type materials at the present time.

At some point the question needs to be asked, "Is nonlinear analysis necessary?"

In the case of early analyses of the Hoe Creek model we found large amounts of yielding (plasticity) in the soft material under the coal being burned, and in the immediate roof materials over the coal. For later runs where we formed an arched roof reflecting the experiment we found no yielding. As we learn more about coordinating roof spall with mechanical loads, and using material properties closer to the field conditions we may find that the nonlinear effects are not needed; alternately we may find that they are highly significant, and important for cases of marginal stability in the overburden rock and soil. We can not say at this time whether either condition will be dominant. What we do know is that the nonlinear codes provide for time-sequenced excavation problems (where the stiffness of the model is time dependant) and linear codes do not, in general, allow this. As long as one must re-form the model stiffness matrix to account for element activation and de-activation, one might as well account for material nonlinearities, if any, at the same time.

We would like to say a little bit at this point about problem capacity and three-dimensional modeling. Most of the models we have solved to date with the aforementioned programs have been two-dimensional problems. A two-dimensional model can represent a cross-section of a long body or a body of revolution, and can account for some 3-D effects. A full 3-D model on the other hand allows for complete modeling but must be at least nine times larger in computer space required. Our 2-D models are generally solved "in-core" meaning that they require not more than 131,000 words of computer space to solve. A 3-D model of similar dimensions would require about 1.2 million words of computer space and is estimated to be about 27 times more costly to solve, hence we (and most others) avoid 3-D models when 2-D models can be used. Some new computers are coming on-line within the next year, like the Cray-1 and the CDC Star 100-A, which will allow nearly 1 million words of "in-core" space. Both machines boast of processing rates on the order of 100 million floating point operations per second (as compared with 15 million for present equipment). We expect that these machines will allow us to make greater use of 3-D modeling in the near future than we have been able to do in the past, and still hold the cost of analysis within reasonable limits.

CONCLUSIONS

In conclusion we can offer the following generalities:

Nonlinear analysis is avilable today for underground modeling, several nonlinear structural programs are available and suitable for the purpose to varying degrees.

Both material and geometric nonlinearities can be accomodated.

Our preference at this time is for a Mohr-Coloumb or Drucker-Prager type material model which allows both cohesion and internal friction to be included in the material "strength."

In some cases material nonlinearities are important, in other cases the model remains elastic.

The codes in use at Lawrence Livermore Laboratory have been calibrated both with elastic theory and with field measurements.

We can economically solve a wide variety of two-dimensional problems, but three-dimensional problems are more costly and must be approached with caution.

While we do not have a perfected model to indicate the precise sequence and rate of overburden collapse, we know that we can plan on removal of all overburden elements in tension, and we are working on methods of determining the removal due to drying.

ACKNOWLEDGEMENTS

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